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Measurement of the Inter-strand Contact Resistance in coils extracted from LHC_IR quadrupole magnets

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Abstract:

This note presents the results of the measurement of the Inter-strand Contact Resistance (ICR) of five cables part of coil sections extracted from the straight sections LHC_IR quadrupole magnets and models. The measured inner coil was extracted from MQXB04, the outer coil was extracted from a short model. Both coils were wound using cables made of Alstom strands and received a standard coil curing. These coil sections were reassembled together with three other coil sections, extracted from short models, into a collared short model. The short model was cooled down to 4.2 K and the ICR was measured at several current values up to 100 A. Each cable sample was instrumented with 8 voltage taps in order to compute the adjacent (R_A) and cross-over (R_C) resistance from the voltage distribution across the cable.

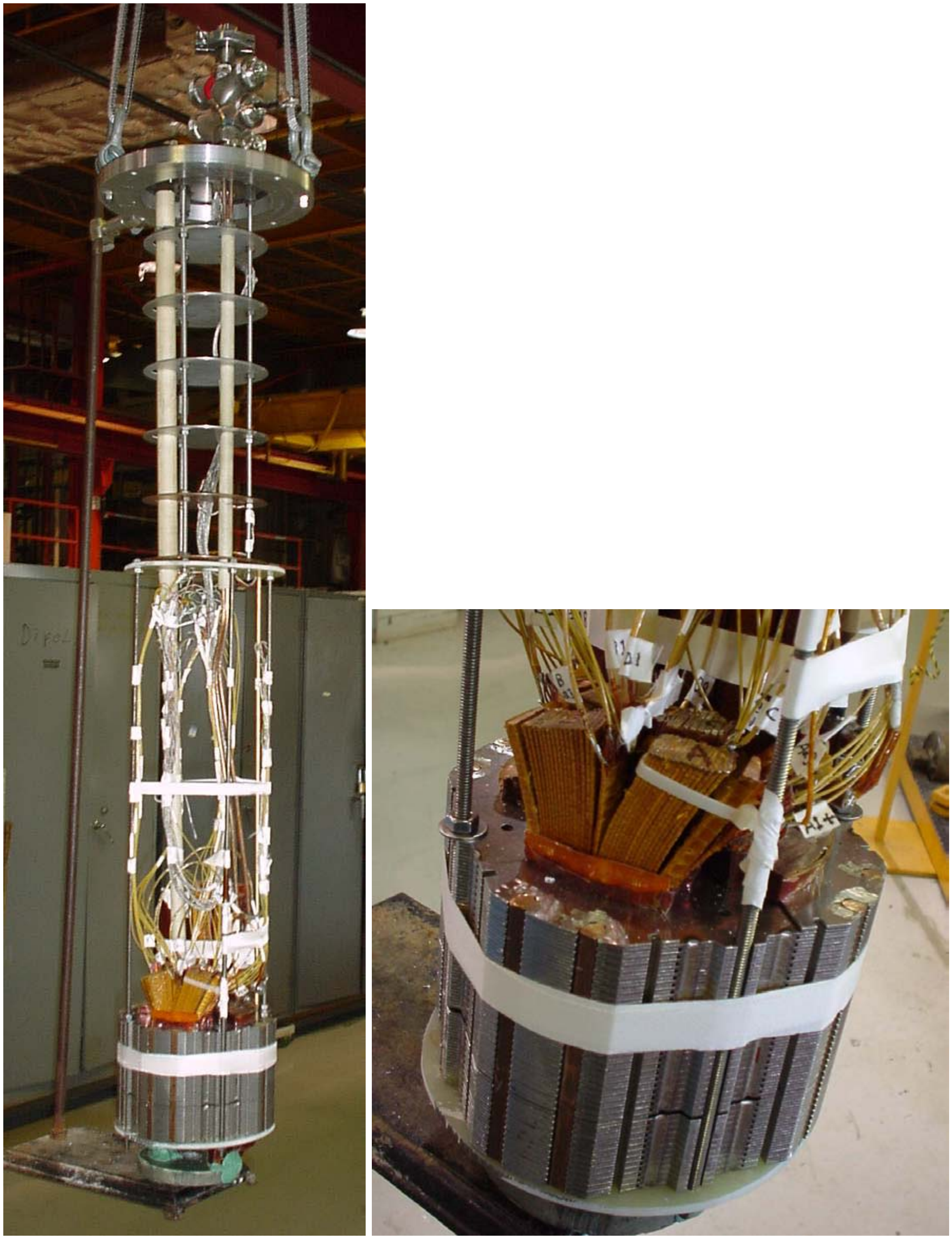


Fig. 1: The sample LHCIR-#1 instrumented (right) and installed on the sample holder (left).

1. SAMPLE DESCRIPTION

The sample was made of a section of the straight part of an inner coil extracted from MQXB04 and of an outer spare coil for short model magnets (HGQs). Both sections were 155-mm long and both coils had been wound with cables made of Alstom strands and received a standard curing (190 C for 10 minutes at low pressure followed by 30 minutes at 135 C under high pressure) [1]. The sample was assembled with three similar dummy samples (extracted from other coils used in short models) and collared following the standard collaring procedure using the short collaring fixture in IB3. The collars covered a section 114-mm long (as the transposition pitch of the inner cable). The coil sections before collaring were about four inches longer than the final sample. After collaring they were cut leaving only few millimeters of cables out of the collars on the bottom of the sample and about 40 mm on the top. The cable cross-section on the bottom of the sample was polished in order to avoid contacts among strands that could cause measurement errors. The top section of the cables was used for instrumentation (Fig. 1).

TABLE 1: Cable parameters (nominal dimensions)

Cable	Inner	Outer
Strand diameter (mm)	0.808	0.648
Number of strands	37	46
Bare cable width (mm)	15.4	15.4
Bare cable thickness: thin-thick edge (mm)	1.32-1.61	1.051-1.241
Cable pitch length (mm)	114	102
Core and/or coating	None	None

The cable parameters are presented in Table 1.

Three cables of the inner coil and two cables of the outer coil were instrumented and measured. Their position is shown in Fig 2. Each measured cable was powered by two leads soldered to opposite strands (with respect to the cable cross section) while eight voltage taps, distributed on the same face of the cable, measured the voltage distribution. The technique used to compute the adjacent and crossover resistance from the voltage distribution across the sample is presented in [2] and [3]. Fig. 3 shows an example of the voltage distribution at different current values. Deviations from a linear dependence could be the sign of poor contact between the leads and the sample causing an overheating of the sample close to the “bad” splice. Because of the large dimensions of this sample a new cryostat was used (with a 7 and ¾ inch aperture). An adapter flange was machined allowing the use of the same top flange used in [3].

2. RESULTS

The sample was cooled down to 4.2 K and the cables were tested, in sequence, starting from low currents (10- 30 A) and ending at the maximum current allowed by the power supply (100 A).

The adjacent and crossover resistances were computed by using them as free parameters in the search of the best fit of the experimental data using the analytical code VIRCAB [4]. In the fit we

TABLE 2: Results.

Sample	Coil layer	**R_A (μΩ)**	**R_C (μΩ)**	**R_{TOT} (μΩ)**	**R_C (μΩ) if R_A= 20*R_C**	Comments
1	Outer	**70**	**400**	**1.9**		
2	Outer			**21**		Poor splice with negative lead
3	Inner	**60**	**540**	**2.7**	**103**	
4	Inner	**80**	**1000**	**5.3**	**208**	Asymmetric voltage distribution
5	Inner	**80**	**750**	**3.3**	**128**	

assumed that the sample was as long as the collared section (i.e. 114 mm) because only this section was under load. The results are presented in Table 2. R_A is the adjacent resistance and R_C the crossover resistance. The total resistance (R_{TOT}) between the strands soldered to the current leads is also shown. The sixth column shows the values of R_C computed by using the total resistance (R_{TOT}) and assuming that R_A is 20 times R_C. These values are reported to facilitate a comparison between the measurements here presented and measurements performed at CERN on samples of production cables for the LHC main dipoles. CERN's results are obtained by averaging three measurements of R_{TOT} on the same sample and then multiplying the average by a "geometry factor" computed under the assumption that R_A is significantly larger than R_C [5].

Figures 4 to 8 show the comparison between the measured voltage distribution in the samples (scaled to 100 A) and the voltages computed by VIRCAB assuming the values of Ra and Rc shown in the legend. All samples were inspected after the test to check the causes of possible problems found during test.

Sample 1 and 5 were fine. Sample 2 had the leads inverted and possibly a poor splice at one of the current leads. The voltage versus current had a maximum deviation from linearity of 30% in the range 10 to 100 A. The results are not reported in Table 2 because they are not reliable. In samples 3 and 4 it looks like that the voltage taps on strand 4 and 7 were reversed, but no evidence of this was found when the sample was checked after test. Sample 4 had a highly asymmetric voltage distribution that could have been caused by a largely non-uniform distribution of contact resistances in the samples.

Figure 9 show the same results of sample 5 presented in Figure 8 together with a fit performed using VIRCAB under the assumption of $R_A = 20 * R_C$.

The fits using VIRCAB were obtained by minimizing the error by hand. A Fortran routine, which will be used to perform this process automatically, is under development.

3. CONCLUSIONS

The three measurements performed on inner cables gave similar results for R_A (60 – 80 μΩ) and within a factor of two for R_C (540 – 1000 μΩ). Unexpectedly the values of the adjacent resistance are significantly lower than the values of the crossover resistance. When the crossover resistance is computed assuming $R_A = 20 * R_C$, then the values of R_C are about a factor two higher than those measured at CERN over four batches of outer cable for the main dipoles (average/batch: 129, 119, 41, 65; sigma/batch; 39%, 47%, 45%, 35%) [6].

The contact resistances have been computed assuming that the sample is as long as the collared part of the cables, because the uncolored part should have significantly higher values. If this assumption is not correct the contact resistances should increase up to 35% more than the values reported in Table 2.

The measured values of R_A and R_C give a quite favorable condition in a magnet, because the adjacent resistance should be sufficiently low to provide stability, and the crossover resistance is sufficiently high to prevent large eddy current heating during ramps.

However these results should be confirmed by further measurements and future samples should be prepared without disassembling the coils after curing. This operation may have in fact increased the interstrand resistance by allowing oxidation of some contact areas. On the other hand the tight bond due to the cured insulation may have prevented or limited the effect of the oxidation on the contact areas. New measurements should try to prevent this possible effect. An alternative method to validate the results here presented, is to compute the expected AC losses and to compare them with experimental values.

REFERENCES

1) R. Bossert, F. Nobrega, D. Chichili, I. Novitski, “LHC IR Quad Long Coil Curing Cycle – Two step”, TD-00-005.
2) G. Ambrosio, E. Barzi, L. Elementi, A.V. Zlobin, *“Measurement of inter-strand contact resistance in epoxy impregnated Nb_3Sn Rutherford cables”,* Proceedings of CEC/ICMC03
3) D. Tooke, G. Ambrosio and L. Elementi *“Interstrand Contact Resistance of Nb3Sn Superconducting Cables Extracted from Magnets”* , TD-04-037
4) Arjan P.Verweij, CERN, private communication
5) David Ricther, CERN, private communication
6) Luc Oberli, CERN, presented at the LHC Project Workshop XIII

APPENDIX - PLOTS

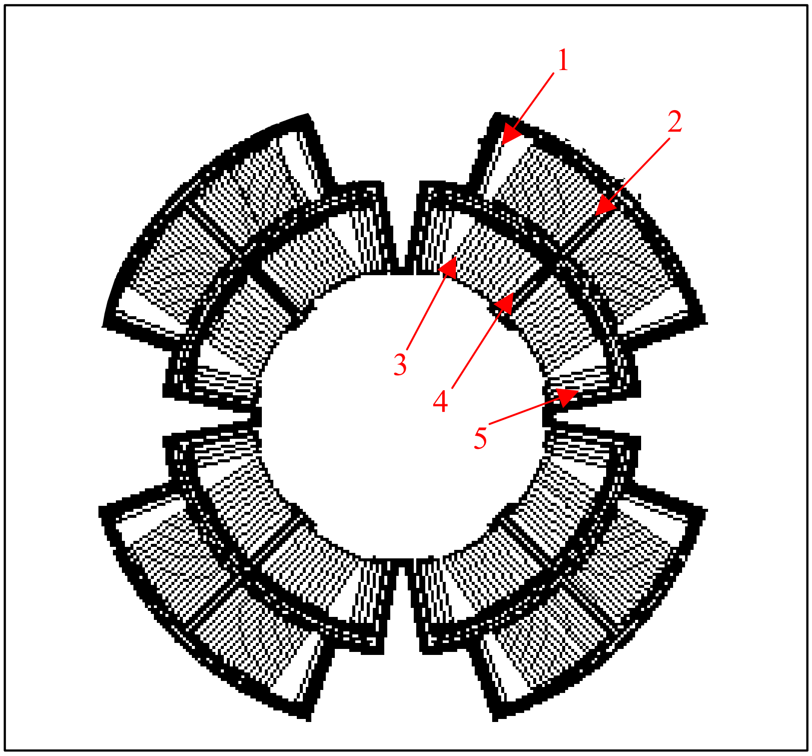


Fig. 2: Position of cables tested.

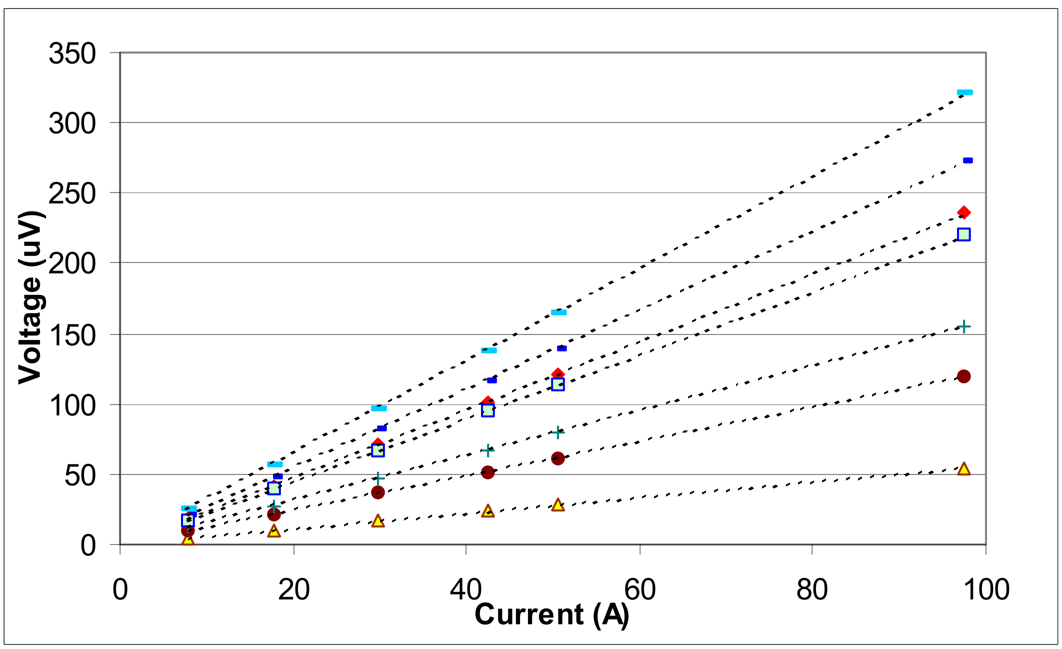
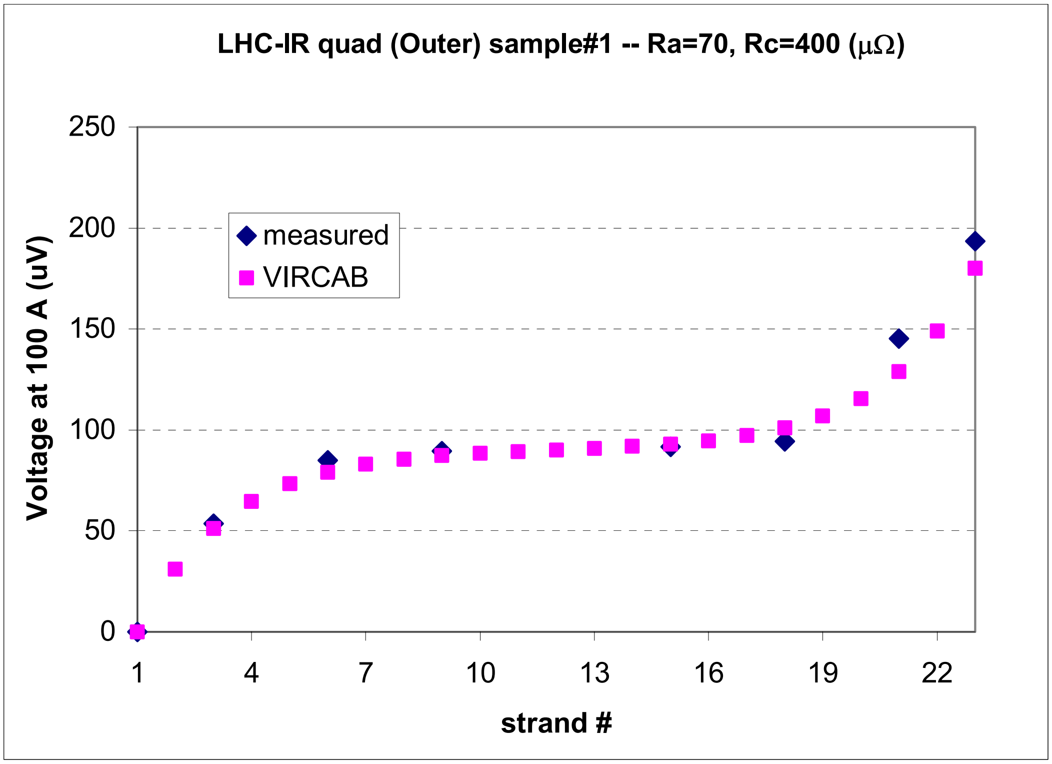


Fig. 3: voltage between the negative lead and the instrumented strands at several current values (sample 5).



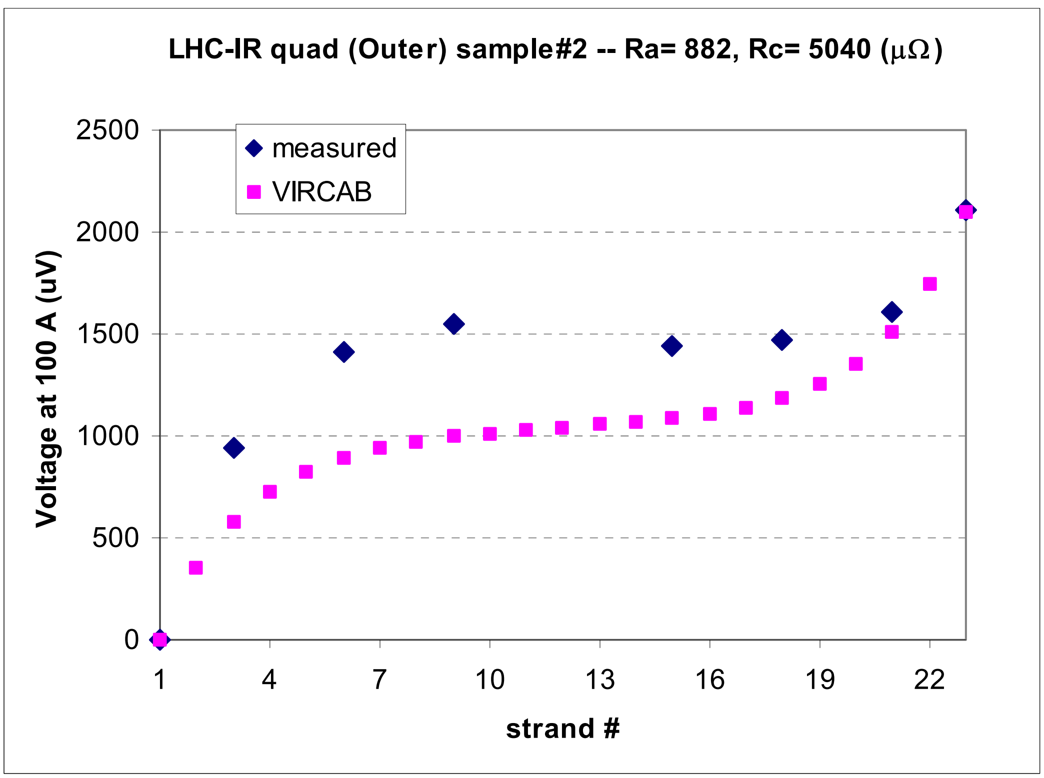
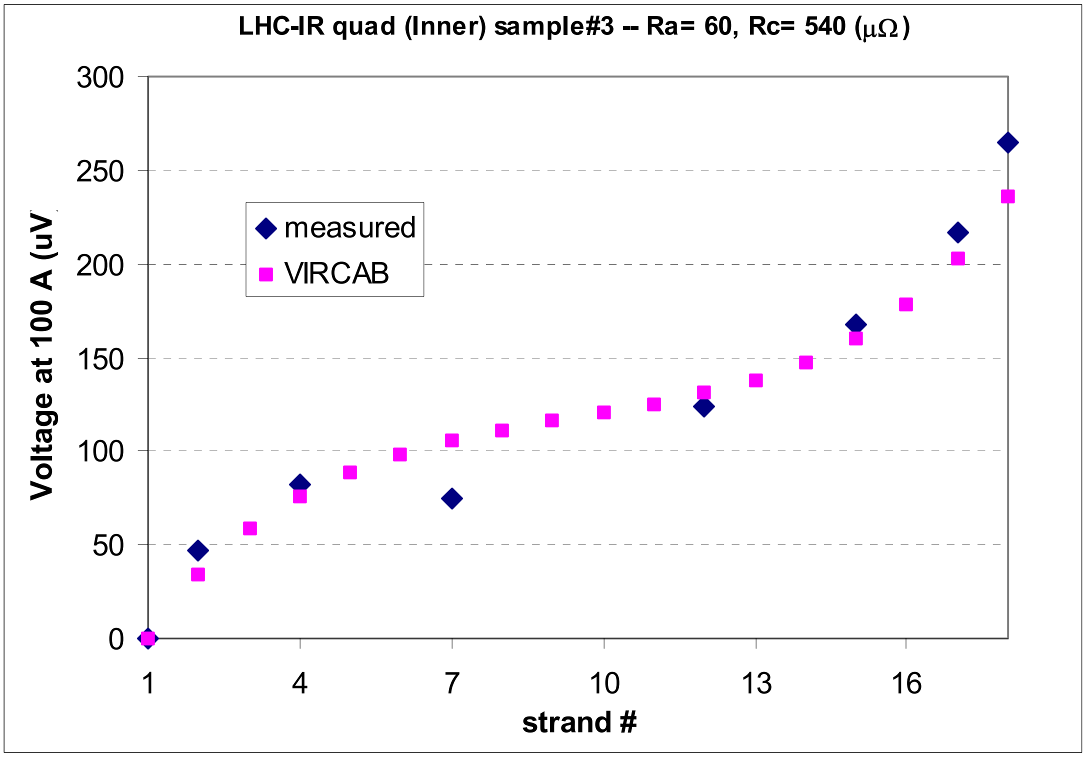


Fig. 4-5: Comparison between the measured voltage distribution (scaled to 100 A) and the voltages computed by VIRCAB assuming the values of Ra and Rc shown in the legend.



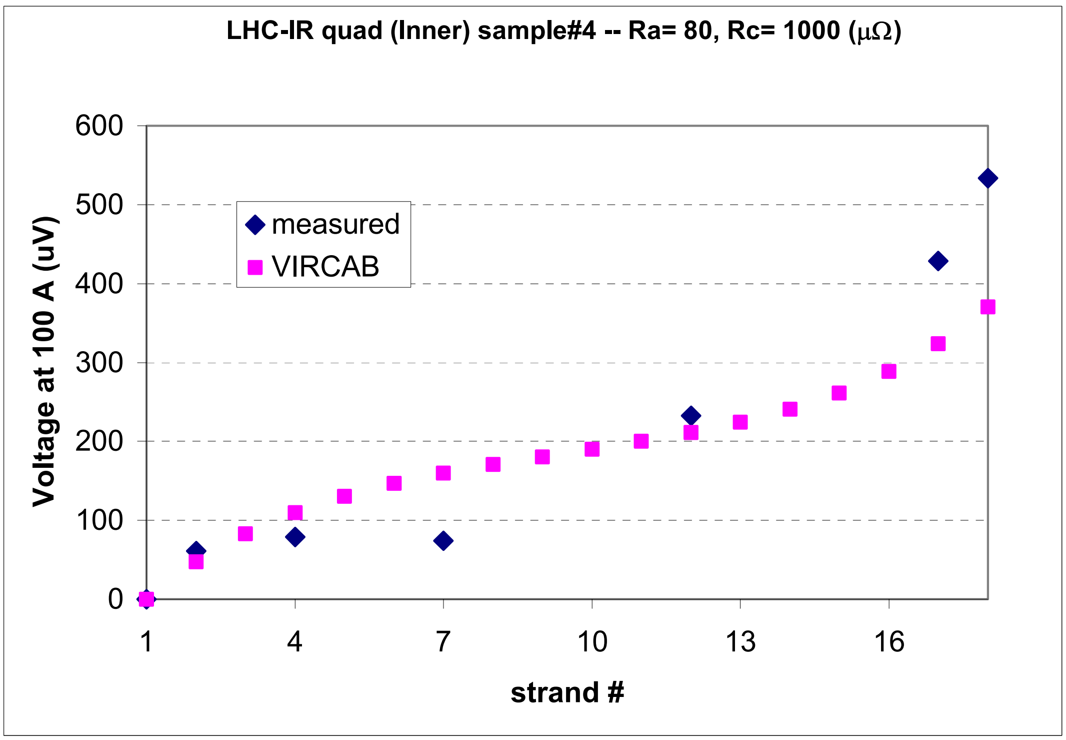


Fig. 6-7: Comparison between the measured voltage distribution (scaled to 100 A) and the voltages computed by VIRCAB assuming the values of Ra and Rc shown in the legend.

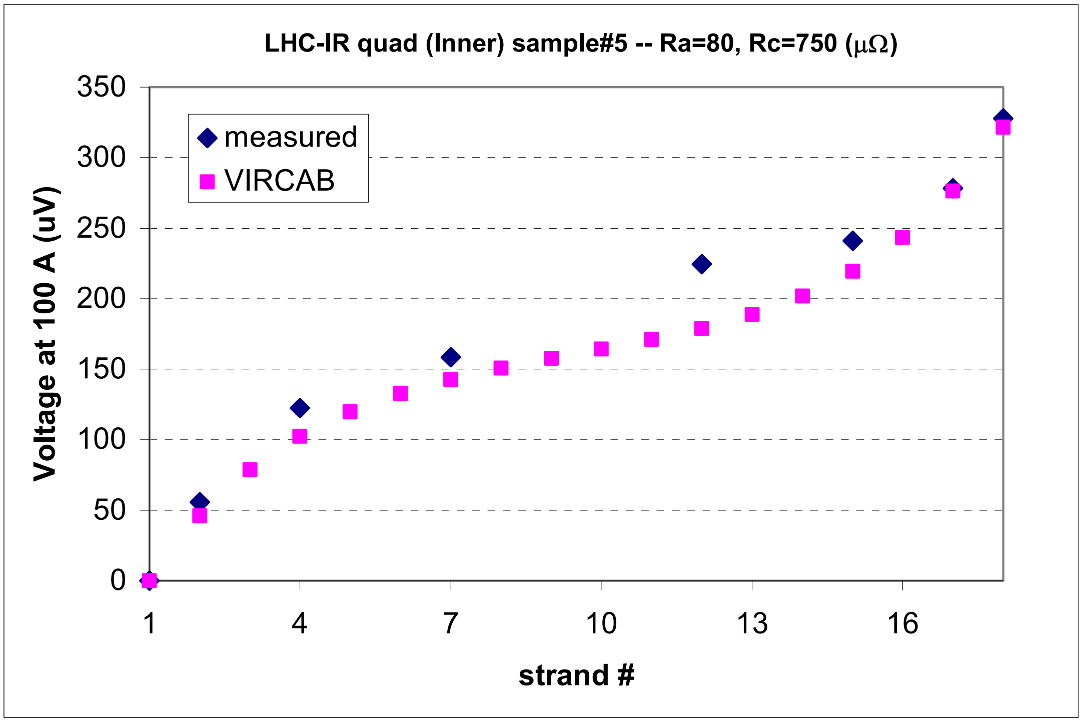


Fig. 8: Comparison between the measured voltage distribution (scaled to 100 A) and the voltages computed by VIRCAB assuming the values of Ra and Rc shown in the legend.

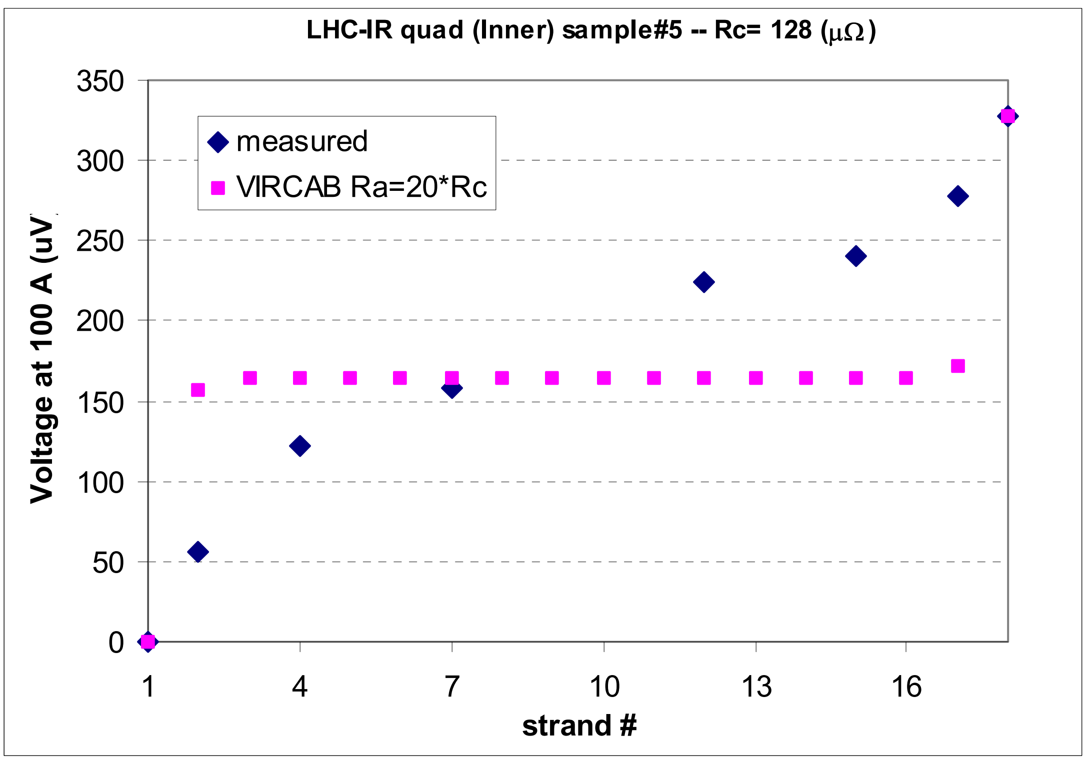


Fig. 9: Comparison between the measured voltage distribution (scaled to 100 A) and the voltages computed by VIRCAB assuming Ra=20*Rc. The value of Rc is shown in the legend.